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Oligocene-Lower Miocene sequences of the Pieniny Klippen Belt and adjacent Magura Nappe between Jarabina and the Poprad River (East Slovakia and South Poland): their tectonic position and palaeogeographic implications

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This paper provides the results of a new litho- and biostratigraphic study from the contact zone between the Magura Nappe and Pieniny Klippen Belt close to Polish-Slovakian border. In the southernmost part of the Krynica facies zone of the Magura Nappe two new lithostratigraphic units have been established: the Poprad Member and the Kremna Formation. The Late Eocene–Oligocene age of the Malcov Formation (NP 19–NP 24) of the Pieniny Klippen Belt has also been confirmed. A Late Oligocene age (Zone NP 25 and lower part of NN1) was determined in deposits belonging to the Poprad Member of the Magura Formation, while an Early Miocene age (upper part of NN1 and NN2 zones) was established for the Kremna Formation. The Late Cretaceous-Middle Miocene geotectonic evolution of the orogenic suture zone, between the Inner and Outer Carpathians, is outlined.

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Key words: Outer Western Carpathians, Pieniny Klippen Belt, lithostratigraphy, biostratigraphy, suture zone.

INTRODUCTION

The fundamental papers of Birkenmajer (1986, 1988) defined three main tectonic stages in the development of the Pieniny Klippen Belt (PKB) to be as follows:

1. The Late Cretaceous (Subhercynian and Laramide) thrust-folding, which produced the nappe structure of the klippen;
2. Early Miocene (Savian) refolding of the Cretaceous nappes and Maastrichtian synorogenic molasse and flysch cover, the development of the southern and northern strike-slip boundary of the PKB, and the formation of the megabreccia and megaboudinage;
3. Middle Miocene (Styrian) compression that produced the system of transverse strike-slip faults in the PKB and the adjacent Outer and Inner Carpathian units.

The previous work and recent discoveries of Lower Miocene deposits in the Magura Nappe (Cieszkowski, 1992; Paul and Poprawa, 1992; Oszczypko *et al.*, 1999; Oszczypko-Clowes, 2001; Oszczypko and Oszczypko-Clowes, 2002; Matašovsky and Andreyeva-Grigorovich, 2002), the Pieniny Klippen Belt (Bakova and Sotak, 2000) and the Central Carpathian Paleogene Basin (Starek *et al.*, 2000) raise questions as to current understanding of the role of the Early Miocene Savian folding and thrusting in the final stages of the geotectonic development of the orogenic suture zone between the Inner and Outer Carpathians.

Our attention was drawn to some of the Paleogene deposits of the PKB and the southernmost part of the Magura Nappe (Fig. 1). This attention focussed on the contact zone between the Magura Nappe and the PKB, close to the Polish-Slovakian border, between the village of Jarabina in the west and the Poprad River in the east. In this area, Late Eocene-Oligocene deposits overlap both the Pieniny Klippen Belt (Ujak–Orlov–Lubotin area) as well as the Magura Nappe (Cirč–Leluchów area). These deposits are known as the Ujak facies. Another characteristic of the area is the occurrence of the "Kremna facies", which reveals connections to both the Magura and PKB facies.

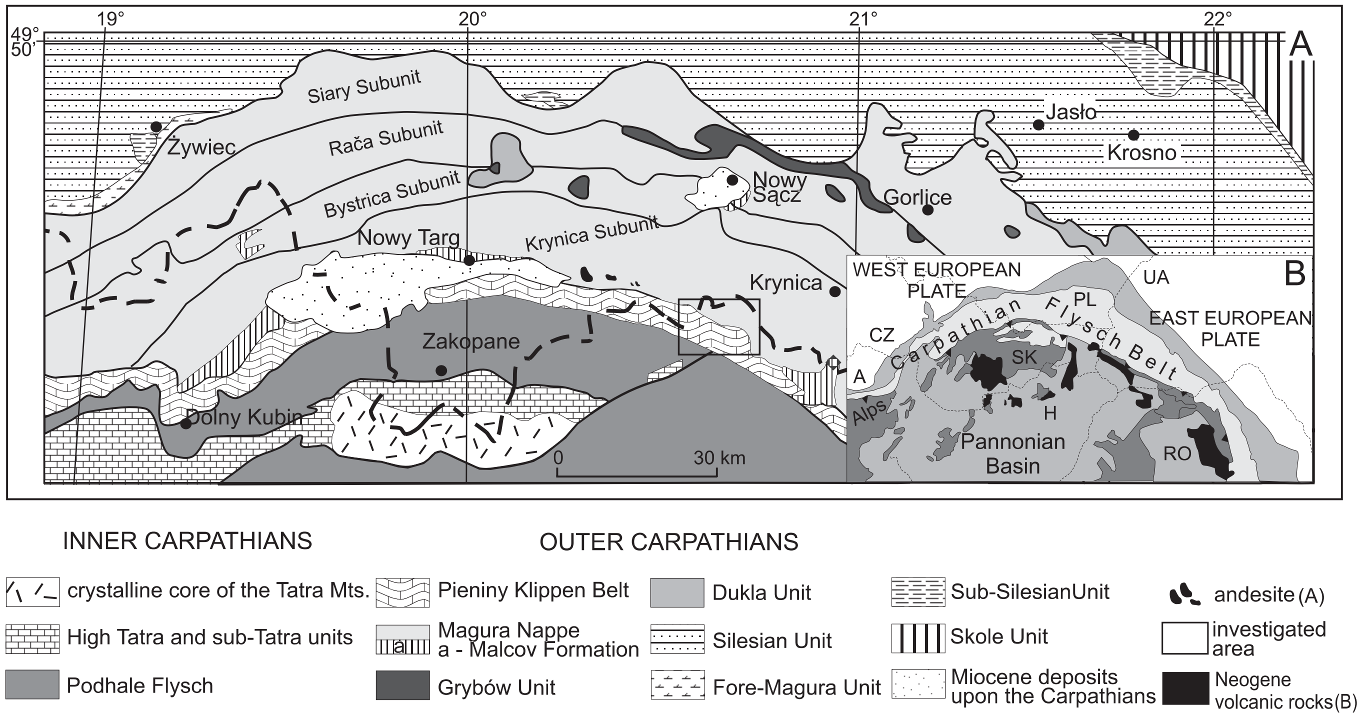

Fig. 1. A — geological map of the middle part of the Western Carpathians (compiled by Oszczypko-Clowes, 2001, simplified); B — position of Outer Carpathians in the Carpato-Pannonian system

PREVIOUS RESULTS

The relationships between the Paleogene deposits of the Inner Carpathians, the Pieniny Klippen Belt and the Magura Nappe still provide important questions.

The first attempt to establish this relationship was made by Książkiewicz and Leško (1959), who documented the same development of the Upper Eocene-Oligocene deposits in the PKB and in the southern part of the Magura Nappe. Two years later, Świdziński (1961*a*, *b*) found "typical Podhale flysch", north of the PKB, near Ujak and Plaveč. According to Świdziński's (1961*a*) interpretation, these deposits overlapped the Pieniny Klippen Belt, and are overthrust by the Magura Nappe. Leško and Samuel (1968) suggested that, during the Late Eocene to Oligocene, the East Slovakian sector of the PKB developed as a transitional zone between the Podhale and Magura flysch. This seaway connection between the Inner and Western Carpathians existed during the Late Eocene–Oligocene. This idea was developed by Stranik and Hanzliková (1968), who described four transitional facies zones (Ujak, Kremna, Lackovce and Inovce) between the Podhale and Magura flysch (Fig. 1).

Ujak facies. The term Ujak facies was established by Roth (1957, fide Stranik and Hanzliková, 1968) in the southeastern part of the Lubovnianska Kotlina near Lubotin. These deposits were later described by Stranik and Hanzliková (1968). According to their work, the lower part of the Ujak facies, up to 200 m thick, is composed of Paleocene–Lower Eocene, coarse-grained sandstones and fine conglomerates with intercalations of dark grey siltstones and thin layers of variegated shales. These deposits were distinguished by Nemčok (1990*a*, *b*) as the Jarmuta-Proč Beds, and are characterized by an occurrence of carbonate flysch and paraconglomerates, which are rich in clasts of Triassic and Jurassic-Lower Cretaceous limestones, radiolarites, exotic crystalline and volcanic rocks. Nemčok (1990*b*) suggests a similarity between the Jarmuta-Proč Beds and the Złatne Member from the Polish segment of PKB (see Morgiel and Sikora, 1974; Birkenmajer and Oszczypko, 1989). Higher up in the sequence a 200–230 m thick succession of Lower to Middle Eocene variegated shales with *Reticulophragmium amplectens* occurs and this is followed by 10 m of *Globigerina* Marls. The upper part of the succession is composed of Menilite Shales (Smereczek Shale Member of the Malcov Formation, see Birkenmajer and Oszczypko, 1989; Oszczypko, 1996; Oszczypko-Clowes, 2001), which are up to 30–40 m thick and developed as brown and dark brown-grey claystones with relics of fish, silicified claystones and cherts (Stranik and Hanzliková, 1968). The succession is terminated by calcareous flysch of the Malcov Formation (Matéjka, 1959, see also Birkenmajer and Oszczypko, 1989), up to 800–1000 m thick, composed of thin to thick-bedded flysch with muscovite-bearing sandstones and grey calcareous claystones. In the lower part of this formation (Orlov and Udol sections), thin beds of laminated limestone ("Jasło Limestones") were found by Świdziński (1961*b*) and Stranik and Hanzlikova (1968). According to Nemčok (1990*b*) these limestones belong to the "Tylawa Limestones". The Ujak facies occurs overlying Mesozoic rocks within a 12 km stretch of the PKB, whereas the width of this belt varies from 1.5 to 10 km. From the north these deposits are overthrust by the Magura Nappe (see Stranik and Hanzliková, 1968, Nemčok, 1990*a*).

Along the Poprad River, the Ujak facies filled the NE–SW trending Plaveč tectonic depression. On the SW and NE edges of the depression the Malcov Formation is in contact with the Central Carpathian Paleogene and the Magura Nappe, respectively. According to interpretations by Stranik and Hanzliková (1968) and Nemčok (1990*b*), the age of the youngest deposits of the Ujak succession was assigned as Priabonian.

Kremna facies. This facies was introduced (Matějka, 1959) in the Pieniny Klippen Belt at the Lubovnianska Vrchovina Highland (Figs. 1 and 2A). Previously these deposits were called: "Nördliche Grenzzone" or "Northern Boundary Zone" (Uhlig, 1890), "flisz graniczny" or "border flysch" (Małkowski, 1922) and "flisz przedskałkowy" and "międzyskałkowy" (Horwitz, 1935). This facies developed at the southern margin of the Krynica (Čerchov) Subunit of the Magura Nappe. According to Stranik and Hanzliková (1968) the Kremna facies, 1200–1600 m thick, is regarded as Paleocene–Upper Eocene, which show a transition between the Klippen and the Magura Paleogene. These authors included the Jarmuta-Proč Beds, composed of coarse-grained calcareous sandstones and conglomerates, as well as sandy-calcareous breccias, intercalated with greenish, grey, and reddish claystones, to the basal portion of the Kremna facies. In their opinion the upper portion of the Kremna facies reveals a similarity to the Frydman Formation in Poland (see Birkenmajer and Oszczypko, 1989), and is characterized by the occurrence of Magura-type sandstones and thin-bedded, flysch layers with Łącko type marlstones. In the upper part of the Kremna facies within the claystone intercalations, Lower to Middle Eocene agglutinated forams have been found as well as the Upper Eocene *Globigerinoides index* and small globigerinas, which "proves the connection of this facies with the Klippen Palaeogene" (Hanzliková, 1959; Stranik and Hanzliková, 1968, table 24, p. 452).

According to Nemčok (1990*a*, *b*) the Kremna succession can be interpreted as the upper part of the Jarmuta-Proč Beds of

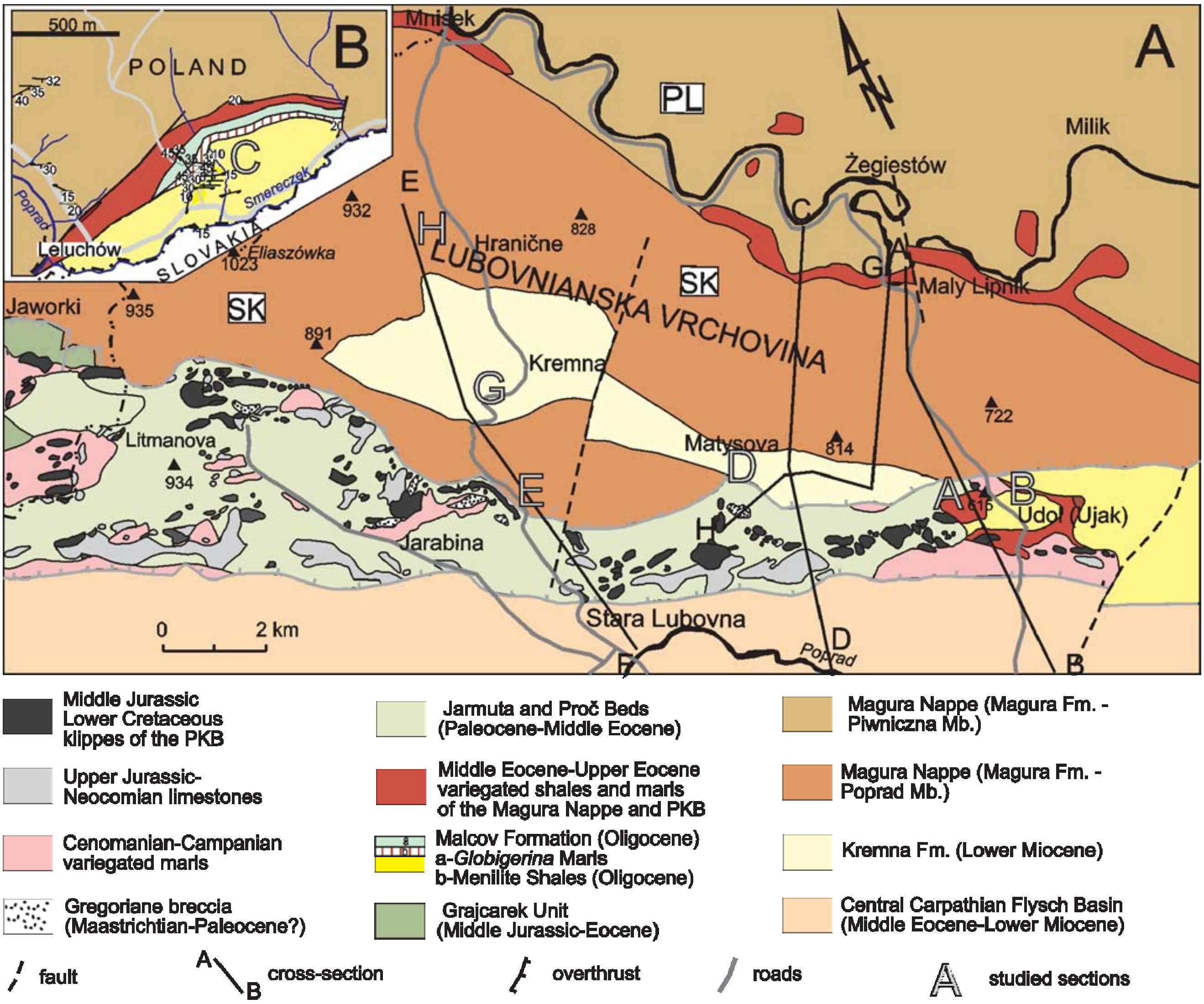

Fig. 2 A — geological sketch-map of the Lubovnianska Vrchovina and eastern part of the Małe Pieniny Mts. (after Nemčok, 1990*a*, supplemented by Oszczypko *et al*., 2004); B — geological sketch-map of the Leluchów area — section C (after Oszczypko-Clowes, 2001)

the PKB, characterized by the occurrence of Łącko type marls, and overthrust by the Magura Nappe. The Lower Eocene age of the Kremna facies was based on poor asemblages of the agglutinated forms and calcareous nannoplankton determinations (Nemčok, 1990*b* and references therein). Recently, on the geological map by Lexa *et al.* (2000) the Kremna Beds were included in the Malcov Formation of the Krynica Subunit.

Paleogene facies of the Krynica Subunit (Magura Nappe). The Krynica Subunit, between Litmanova and the Poprad Valley, is composed of Eocene deposits (Nemčok (1990*a*, *b*), belonging to the Čerhova Beds (Middle Eocene), variegated beds (Middle/Upper Eocene) and the Strihov Beds (Middle/Upper Eocene) (Figs. 1 and 2A). The Cerhov and Strihov beds are represented by thick-bedded flysch with sporadic mudstone/claystone intercalations, while the variegated beds are dominated by red shales, locally with Mn-concretions and thin-bedded sandstones. According to the formal lithostratigraphy established by Birkenmajer and Oszczypko (1989), Oszczypko *et al.* (1990) and Oszczypko-Clowes (2001), the Čerhova, variegated and Strihov beds belong to the Piwniczna, Mniszek and Poprad members of the Magura Formation, respectively. In the Leluchów section (Fig. 2B) the Mniszek Member passes upwards into the Malcov Formation (Upper Eocene–Oligocene) of the Ujak–Orlov–Plavec–Lubotin and Leluchów Syncline. Birkenmajer and Oszczypko (1989) described the Leluchów section as a sedimentary transition from the Magura Formation (Lower–Middle Eocene) to the Malcov Formation of the Ujak succession. According to their interpretation the *Globigerina* Marls (Priabonian–Rupelian) and Menilite Shales (Rupelian) could be established as the Leluchów and Smereczek members of the Malcov Formation, respectively (see also Oszczypko *et al.*, 1990).

GEOLOGICAL SETTING

The area studied is located in the Lubovnianska Vrchovina Highland (Eastern Slovakia) and southern slope of the Beskid Sądecki Range (Poland), between Jarabina in the west and the Poprad River in the east and north-east. The central part of this area belongs to the PKB suture zone, bounded by the Central Carpathian Paleogene (Podhale Flysch), and the Magura Nappe from the south and north, respectively. The Pieniny Klippen Belt occurs in a narrow zone, whose width varies from 4 km between the Polish/Slovak border and Jarabina and *ca*. 2 km SE of Jarabina (Figs. 1 and 2A). The main characteristic elements of the PKB landscape are the klippen of the Jurassic-Neocomian hard rocks, which form the hills and ridges and are surrounded by Upper Cretaceous-Paleogene soft rocks (Fig. 3A). The development of the Bajocian-Maastrichtian rocks of the PKB, at least 400 m thick, generally coincides with the Czorsztyn succession. The Mesozoic klippen are dispersed mainly within the Paleocene-Lower Eocene Jarmuta-Proč Beds (Fig. 4).

In many places, at the base of the Jarmuta-Proč Beds, there occurs the Gregorianka sedimentary breccia (Nemčok, 1990*a*, *b*), which is up to 30 m thick. The breccia (Fig. 3C) is composed of different sized angular rock fragments, mainly Bathonian-Bajocian crinoidal limestones, Tithonian-Berriasian-Aptian limestones and Upper Cretaceous variegated marls. The latter are dispersed in a psammitic matrix locally with Paleocene foraminifers.

Along the northern margin of the PKB, the Jarmuta-Proč Beds (Fig. 3D) are covered by two lobes of the Kremna facies. The larger of the two (6 x 2.5 km) is known from the Kremna area, while the smaller one (3 x 1 km) is from the village of Matysova (Fig. 2). In both of these locations Mesozoic klippen do not occur. South-east of Matysova, the position of the Kremna facies is occupied by the Ujak facies, which occurs in a section of the belt up to 1 km in width. Towards the SE, the belt widens to 5 km in the Orlov section and up to 10 km in the Leluchów–Cirč area. In the Lubovnianska Vrchovina Highland, the Pieniny Klippen Belt is separated from the Magura Nappe and Central Carpathian Paleogene by subvertical, north-dipping inverse faults (Nemčok, 1990*a*). The relationship of the Ujak facies to the Pieniny Klippen Belt was well documented on the geological map by Nemčok (1990*a*). Accordingly, in the Udol area basal portion of these facies covers different lithostratigraphic units of the PKB or the Proč-Jarmuta Beds. A similar interpretation was also given by Świdziński (1961*a*, *b*). This may possibly suggest that the "klippen" structure of the PKB was formed before the Mid Eocene, and then was unconformably onlapped by the Middle/Upper Eocene-Oligocene Ujak facies.

In the north, the Pieniny Klippen Belt contacts with the Magura Nappe along a north-dipping thrust (Nemčok, 1990*a*). The deposits in the contact zone are not older than the Eocene deposits of the Magura Nappe, which suggests that the thrust is a subvertical, inverse fault (Fig. 5). This part of the Magura Nappe, belonging to the Krynica (Čerchov) Subunit, forms a large synclinal zone. The Krynica Subunit, which lies SW of the Poprad River, is composed of the Magura Formation (Middle Eocene to Oligocene, see Birkenmajer and Oszczypko, 1989). This formation reaches 2000–2500 m in thickness in the Krynica Subunit. The Magura Formation is represented by thick-bedded turbidites and fluxoturbidites, deposited in distributary channels and lobes of the middle submarine fans. In Poland the Magura Formation is subdivided into the following members: the Piwniczna Sandstone, Mniszek Shale and Poprad Sandstone (Birkenmajer and Oszczypko, 1989). In the Ondavska Vrchovina Highland area these sub-divisions correspond to the Čerchov, variegated and Strihov Beds, respectively (Nemčok, 1990*a*, *b*). The Strihov Beds (Upper Eocene) were correlated with the lower Malcov Formation by Nemčok (1990*a*, *b*).

In the area studied, the boundaries between these members run approximately parallel to the Poprad River (Figs. 1 and 2A). The sandstone members (Piwniczna and Poprad) are separated by thin-bedded flysch with red shale intercalations of the Mniszek Shale Member. Additionally the uppermost part of the Piwniczna Member was sampled in the Milik quarry near Muszyna town (see Oszczypko *et al.*, 1990).

During our studies we found a sedimentary transition between the Poprad Sandstone Member and the Kremna facies. This enables us to establish the Kremna Formation as the youngest lithostratigraphic unit of the Krynica succession in the Magura Nappe. This newly established formation is described in the next chapter.

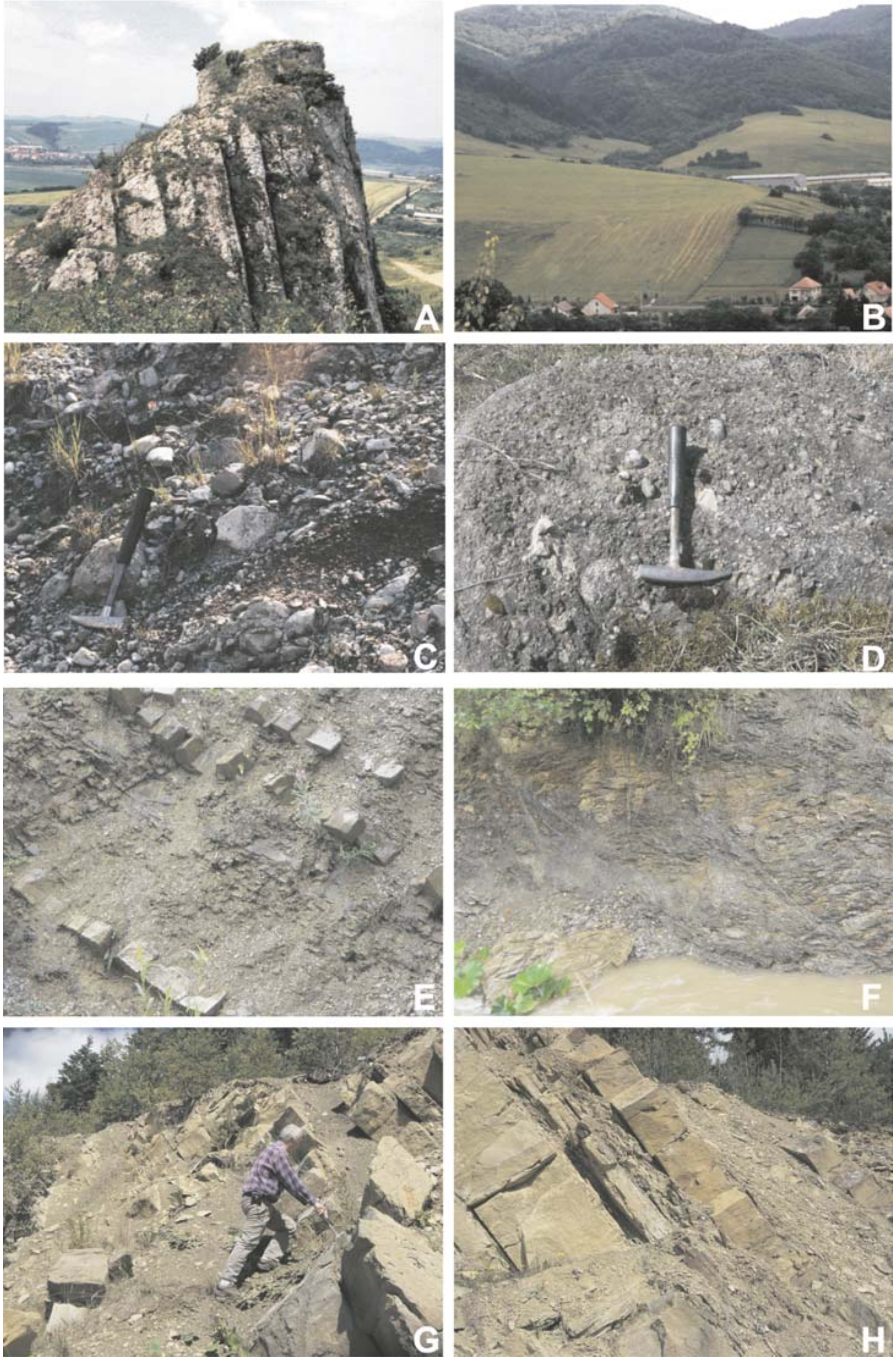

Fig. 3. A — isolated klippen near the Udol village. Sub-vertical dipping of the Czorszyn Limestone Fm. (Czorsztyn succession) located at the contact between the Malcov Formation on the right and the Central Carpathian Paleogene on the left; B — the eastern termination of the Plaveč-Leluchów-Ruska Vola Basin. View from north (Leluchów) at the area of distribution of the Malcov Formation (Oligocene) surrounded to the S by the Magura Formation; C — section Udol A. Cobbles of Late Jurassic-Early Cretaceous limestones in the matrix of Late Cretaceous Marls; D — section Udol A. Blocks of the Proč Conglomerates (Paleocene–Lower Eocene); E — Matysova D section. Upper part of the Poprad Member of the Magura Formation. The Menilite-like shales within thick-bedded sandstones; F — detail of Figure 3E. Locality of the samples 13/03, 14/03 and 15/03; G — Jarabina E section. Uppermost part of the Poprad Member. Thick-bedded sandstones with large mudstone clast, intercalated with marly mudstones. South limb of small anticline; H — Jarabina E section. Uppermost part of the Poprad Member. Thick-bedded sandstones with large mudstone clast, intercalated with marly mudstones. North (imbricated) limb of small anticline

STUDIED SECTIONS

During the fieldwork we studied and sampled several formations of the Ujak facies in the Udol* (A and B) sections and Leluchów C sections), the Poprad Member of the Magura Formation (Matysova D, Jarabina E and Hranicne F sections) and the Kremna facies (Matysova D and Kremna G sections) (Fig. 2A).

Ujak facies. Rocks of the Ujak facies were sampled in the Udol (A, B) and Leluchów (C) sections.

In the Udol area the Ujak facies occur close to a contact zone between the Magura Nappe and the Pieniny Klippen Belt. This section was also described by Stranik and Hanzliková (1968) see also Nemčok (1990*a*, *b*).

* Udol and Ujak are the names of the same village. The first of these is presently in the use, whereas the second name is known from the literature. In this paper the name Ujak will be used only in the context of the Ujak facies.

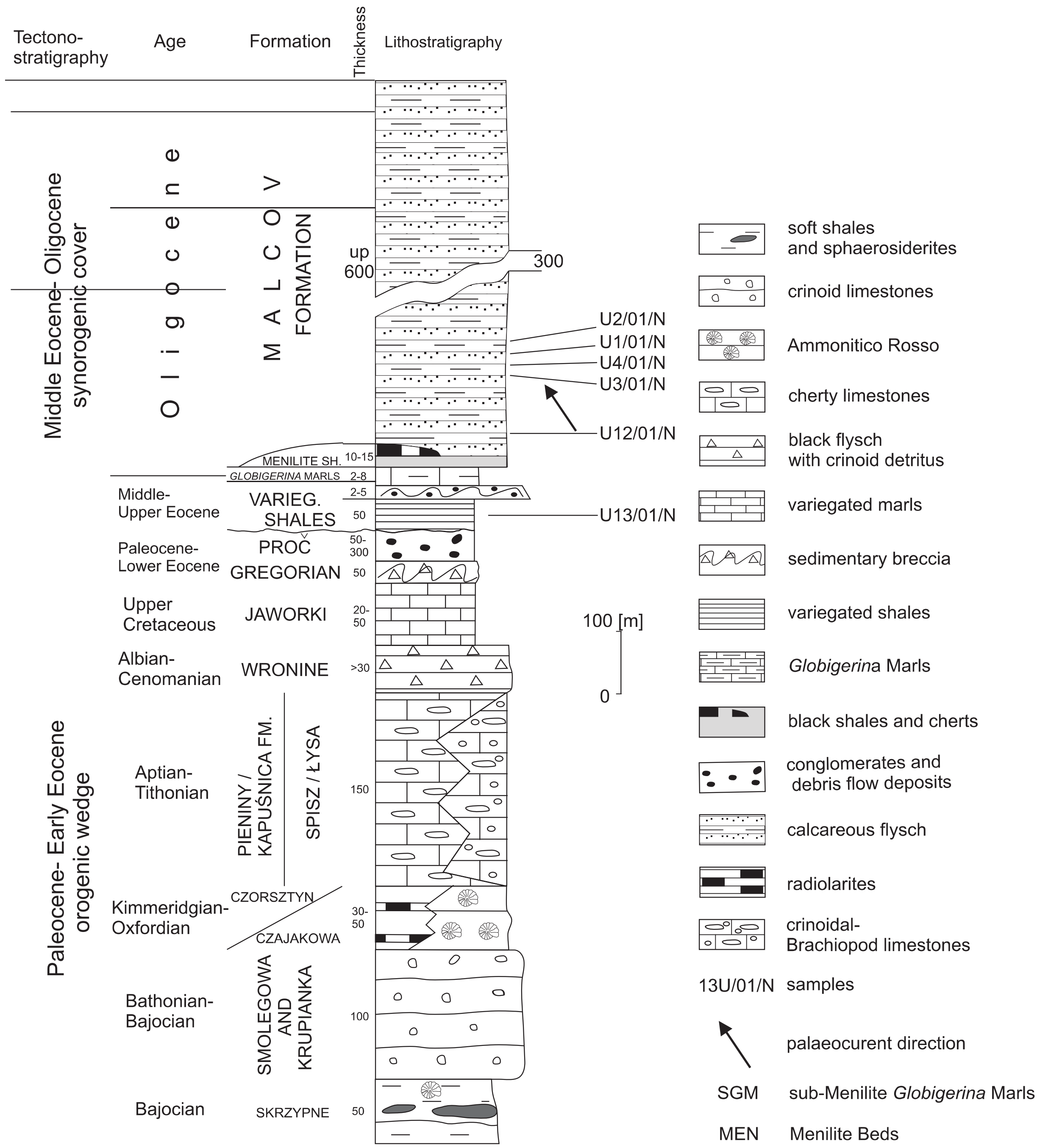

Fig. 4. General lithostratigraphic column of the Pieniny Klippen Belt in the Lubovnianska Vrchovina Range (based on Nemčok, 1990*a*, *b*, modified)

Section A (road-cut exposure) is situated 1 km north from the centre of the village of Udol, close to a small chapel (N 48° 18.207', E 20° 47.623') (Figs. 2A and 6). The position and age of the Mesozoic strata in this section were recently studied by Oszczypko et al. (2004). This section, 180 m long, revealed four sub-vertically dipping thrust sheets, composed of Albian-Cenomanian black flysch and Cenomanian-Maastrichtian grey and variegated marls (Fig. 6). From the south, the Lower and Upper Cretaceous deposits of the PKB are tectonically bounded by two thrust-sheets, which are composed of Middle-? Upper Eocene variegated marls and grey marly shales with intercalations of thin-bedded micaceous sandstones of the Malcov Formation. From these deposits samples U12/01/N and U13/01/N were taken.

Section B revealed Malcov Formation deposits in the Udol creek near the church in Udol. Four samples were taken from this section (Fig. 7).

The Leluchów C section (Krynica Zone) studied is situated on the left bank of the Poprad River, close to the Polish-Slovak border (Figs. 2B and 7). The main section is located along the creek and path, close to the Orthodox Church. The litho- and biostratigraphical results from the Leluchów section were pub-

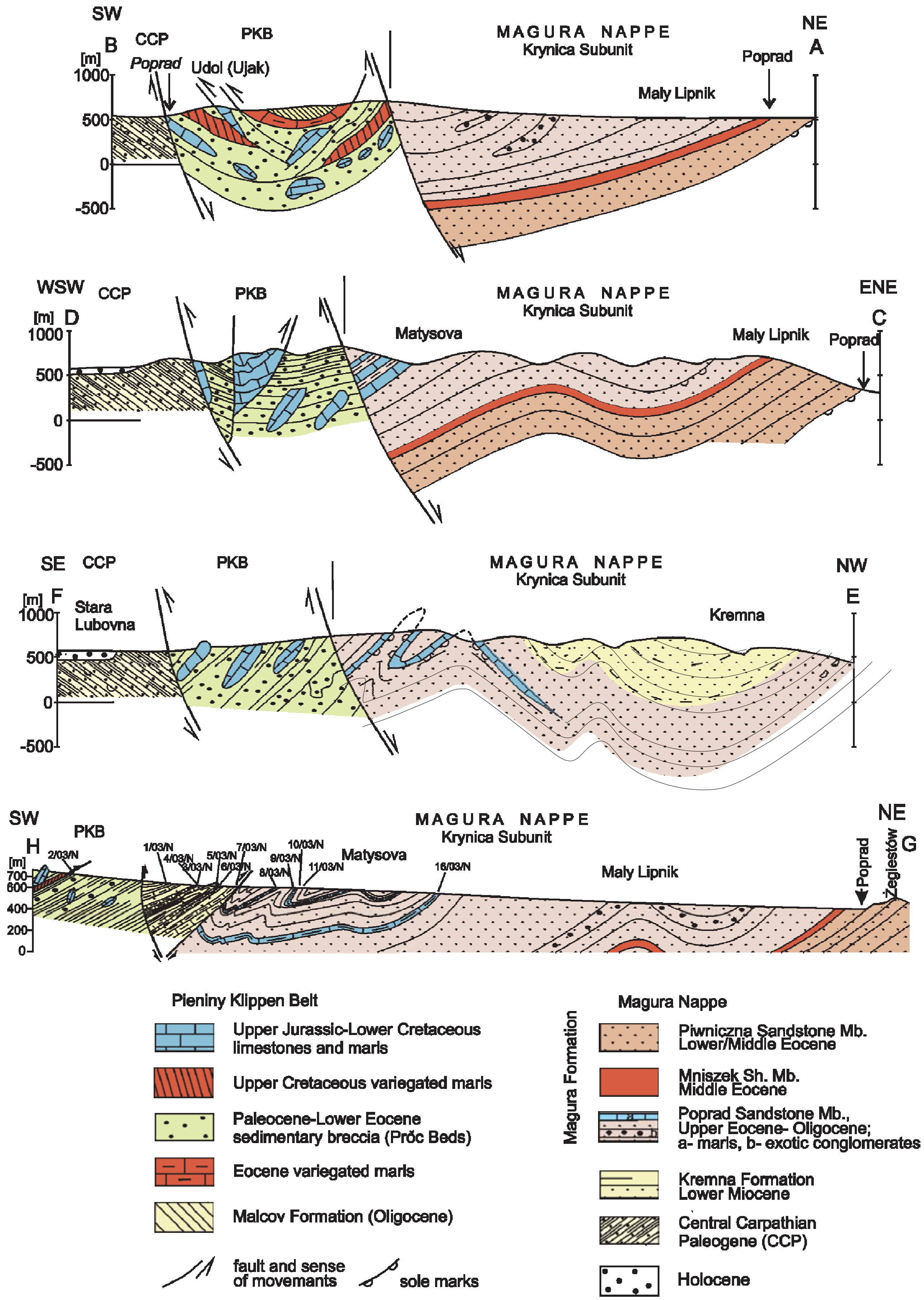

Fig. 5. Simplified geological cross-sections through the Lubovnianska Vrchovina Range

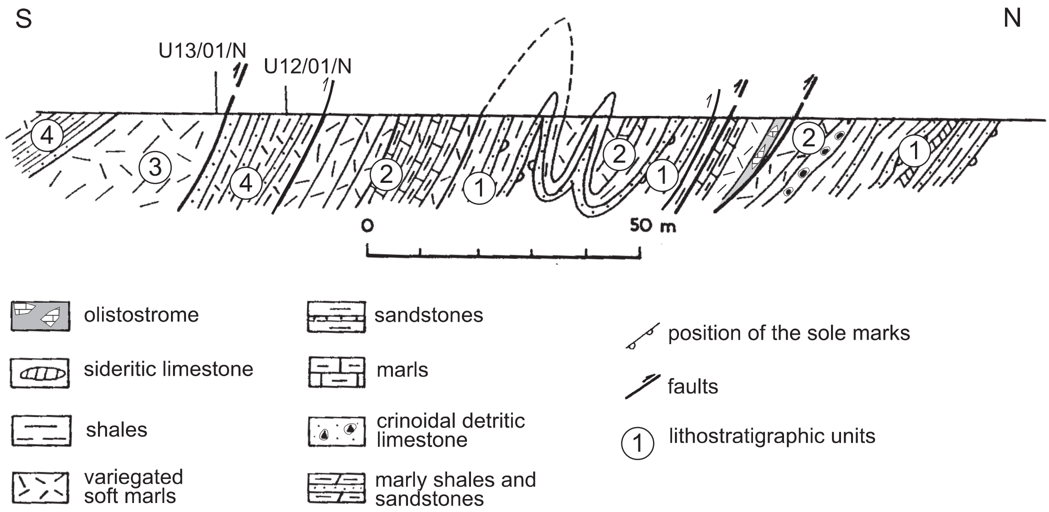

Fig. 6. Geological cross-section in the road-cut near Udol section A (after Oszczypko *et al.*, 2004, simplified)

1 — "black flysch" (Albian–Cenomanian); 2 — grey and variegated marls (Cenomanian–Maastrichtian); 3 — variegated marls (Middle–Late Eocene); 4 — Malcov Formation (Oligocene); samples: U12–U13/01/N

lished by the second author (Oszczypko, 1996; Oszczypko-Clowes, 1998, 1999, 2001). The lowest part of the Leluchów section consists of thick-bedded (0.4–2.5 m) muscovite-bearing sandstones and conglomerates. These strata belong to the Piwniczna Sandstone Member of the Magura Formation. The contact between Piwniczna Member and the overlying marly shales of the Leluchów Marl Member (known also as Sub-Menilite *Globigerina* Marls; see Birkenmajer and Oszczypko, 1989) is not exposed in the section studied (few m break in exposure). The basal 0.5 m to 2.5 m thick portion of the Leluchów Marl Member with numerous calcite veins is covered by a 4 m-thick unit of red, greyish-green, greenish and olive marls. The absence of the Mniszek Shale Member of the Magura Formation suggests a tectonic contact between the Piwniczna Member and the Leluchów Marl Member in the section. According to Blaicher and Sikora (1967), between these units there is a minimum 50 m thick succession of thin-bedded flysch with intercalations of red shales containing *Reticulophragmium amplectens* (Mniszek Shale Member of the Magura Formation, see Birkenmajer and Oszczypko, 1989). The Leluchów Marls Member is covered by, at least, a 19 m thick Smereczek Shale Member, represented by dark menilite-like shales (see Blaicher and Sikora, 1967). The lowermost portion of this member reveals a marly development with a few tuffite intercalations ("Gąsiory"? level), and a thin (2–5 cm) intercalation of hornstones at the top. In this part of the section two thin intercalations of detritital Bryozoa-Lithothamnium limestones were found. The upper portion of the Menilite Shales consists of black non-calcareous, bituminous shales with a few layers of coarse-grained, thick-bedded sandstone. At the top of the Smereczek Shale Member, there occurs a 25 m package of coarse-grained, muscovite-bearing thick-bedded sandstones (1–1.5 m) with intercalations of green marly claystones and medium-bedded sandstones with T_{abc} Bouma intervals. These sandstones could be regarded as the equivalent of the Poprad Member. In the uppermost part of the Leluchów section there occur thin-bedded turbidites of the Malcov Formation. These flat-laying, south-dipping strata consist of Krosno Formation-like, dark grey marly shales with intercalations of thin-bedded (10–12 cm), cross-laminated calcareous sandstones.

Poprad Member. The Poprad Member was sampled in the lower part of the village of Matysova (Fig. 2A), section D (GPS N 49° 18.864'; E 20° 46.513', 542 m a.s.l.). This exposure is situated at the right bank of the Lipnik creek, about 200 m below the top of the Poprad Sandstone Member (Strihov Beds, see Nemčok, 1990a). This part of section is composed of coarse to very coarse-grained, thick-bedded (0. 40 to 2 m thick) sandstones, with sporadic intercalations of dark grey, marly mudstones (Fig. 3E, F).

Similar deposits were found along road cutting no. 68 (Stara Lubovna–Mniszek–Piwniczna). The next exposures (E) are located *ca*. 0.5 km beneath the top of Sedlo Vabec Hill. Heading down (Stara Lubovnia direction) from the point (GPS N 49° 20.585'; E 20° 40.658'; 750 m a.s.l.) are the 500 m long exposures, located on the west site of the road (Fig. 2A). The first 200 m display an imbricated, north-vergent anticlinal fold, composed of medium-bedded turbidites (Fig. 3G, H) with intercalations of thick-bedded, muscovite-bearing sandstones (0.5–1.2 m thick). A characteristic feature of these deposits is the occurrence of Magura-type sandstones and 1. 5–2.0 m thick intercalations of dark grey to greenish calcareous Łącko Marl-type mudstones (Fig. 8A, B). On the south limb of the anticline, these deposits pass upwards into thick- and very thick-bedded Magura-type sandstones, which reveal a palaeocurrent direction towards the W. The same lithofacies, represented by green-grey calcareous mudsones with intercalations of calcareous sandstones and rich in small clasts of *Lithothamnium*, were observed in the village of Hranične at the small bridge on the Elašovka brook. These deposits were included by Nemčok (1990*a*, *b*) in the Jarmuta-Proč Beds (Paleocene–Lower Eocene) of the PKB. The flysch deposits described by us from the Stara Lubovna–Mniszek road cutting resemble the Frydman Formation (Lower Eocene) from the Krynica Zone (peri-PKB area near Czorsztyn, see Birkenmajer and Oszczypko, 1989) as well as the "...Cisówka Beds from the Złatne succession of PKB..." (Morgiel and Sikora, 1974, see also Złatne Member, Birkenmajer and Oszczypko, 1989). Morgiel and Sikora (1974) documented small globigerinids in these beds as being of Eo-Oligocene age.

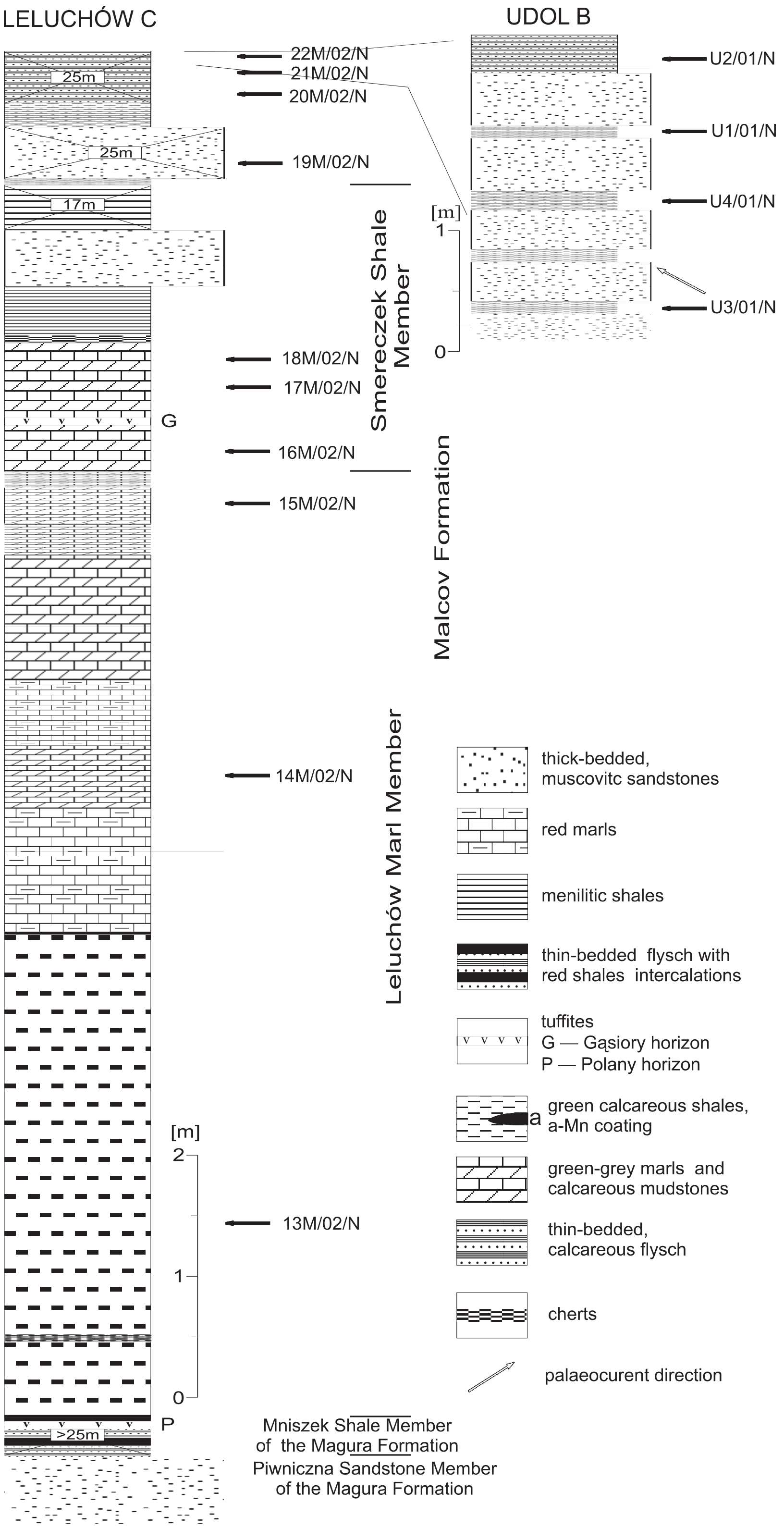

Fig. 7. Lithostratigraphic columns of the "Ujak facies" in the Leluchów C section (after Oszczypko-Clowes, 2001, simplified) and Udol B section

KREMNA FORMATION (NEW NAME)

H i s t o r y . — See above, the description of the Kremna facies.

N a m e . — After the hamlet of Kremna 2.5 km S from village of Hraničné and 6 km N from Stara Lubovna (Fig. 2A).

T y p e l o c a l i t e s . — Road cut near the Tourist Hotel in Kremna, section G (GPS N 49° 21.331'; E 20° 41.148'; 670 m a.s.l., Fig. 2A).

R e f e r e n c e s e c t i o n . — The Lipnik Stream in the Matysova section D, located between GPS coordinates N 49° 19.330'; E 20° 44.802'; 627 m a.s.l. and GPS N 49° 18.780'; E 20° 46.257'; 548 m a.s.l.) (Fig. 2A).

T h i c k n e s s . — From 200–300 m in the Matysova section (Fig. 8D), to 500–600 m in the Kremna section (Fig. 5)

D o m i n a n t l i t h o l o g y . — The Kremna Formation is represented by thin-to-medium-bedded turbidites (T_{bc}) with intercalations of thick-bedded (1.0–2.0 m) massive sandstones, locally with mudstone clasts (Figs. 8D, F and 9). The sandstones are sandwiched with 1.5–8 m thick packages of dark grey marly shales and laminated marls. These medium- to coarse-grained sandstones are usually calcareous and reveal a palaeotransport towards the NW and N.

B o u n d a r i e s . — Lower boundary transitional from thick-bedded turbidites of the Poprad Sandstone Mb. of the Magura Formation (Fig. 9). Upper boundary is erosional.

D i s t r i b u t i o n . — The southern part of the Krynica Subunit of the Magura Nappe in Poland and Slovakia.

A g e . Lower Miocene (see chapter the following on biostratigraphy).

E q u i v a l e n t s . — Bystre Formation (Cieszkowski, 1992), Zawada Formation (Oszczypko *et al.*, 1999, Oszczypko-Clowes, 2001, Oszczypko and Oszczypko-Clowes, 2002), Kochanovce Beds (Matašovsky and Andreyeva-Grigorovich, 2002).

R e m a r k s . — The Kremna Formation was sampled in the Matysova and Kremna sections (Fig. 9).

STUDY OF CALCAREOUS NANNOFOSSILS — RESULTS

All samples were prepared using the standard smear slide technique for light microscope (LM) observations. The investigation was carried out under LM — *Nikon–Eclipse E 600 POL*, at a magnification of 1000 X using parallel and crossed nicols. Several of the specimens photographed in LM are illustrated in Figure 10.

The samples examined contain fairly well preserved and diverse calcareous nannofossils. The relative abundance of

Fig. 8. A — Jarabina E section. Uppermost part of the Poprad Member. Thin to medium-bedded sandstones with intercalations of Łącko-type marlstones. Crest of small anticline. B — Jarabina E section. Uppermost part of the Poprad Member. Thin to medium-bedded sandstones with intercalations of Łącko-type marlstones. Crest of small anticline. C — exposures of the Poprad Member along the Ruska Vola–Cirč road. D — Matysova section D, dark marly shales of the Kremna Formation (Lower Miocene). E — Jarabina E section. Poprad Member, thick-bedded sandstones with intercalation of marly mudstones. F — Kremna section G. Dark marly shales of the Kremna Formation (Lower Miocene). Medium-bedded T_{abc} turbidites, rich in small limestone clasts

these nannofossils is usually medium to high and is illustrated in Tables 1 and 2.

UJAK FACIES

Red marls. The sample examined (U13/01/N, Figs. 2A and 6) contains a moderately abundant nannofossil assemblage (6–8 specimens per observation field), which is dominated by placoliths. The autochthonous assemblage consists of *Coccolithus pelagicus* (Wallich), *C. eopelagicus* (Bramlette et Riedel), *Cyclicargolithus floridanus* (Roth et Hay), *Chiasmolithus gigas* (Bramlette et Sullivan), *C. grandis* (Bramlette et Riedel), *Dictyococcites bisectus* (Hay, Mohler et Wade), *Discoaster barbadiensis* Tan, *D. tanii* Bramlette et

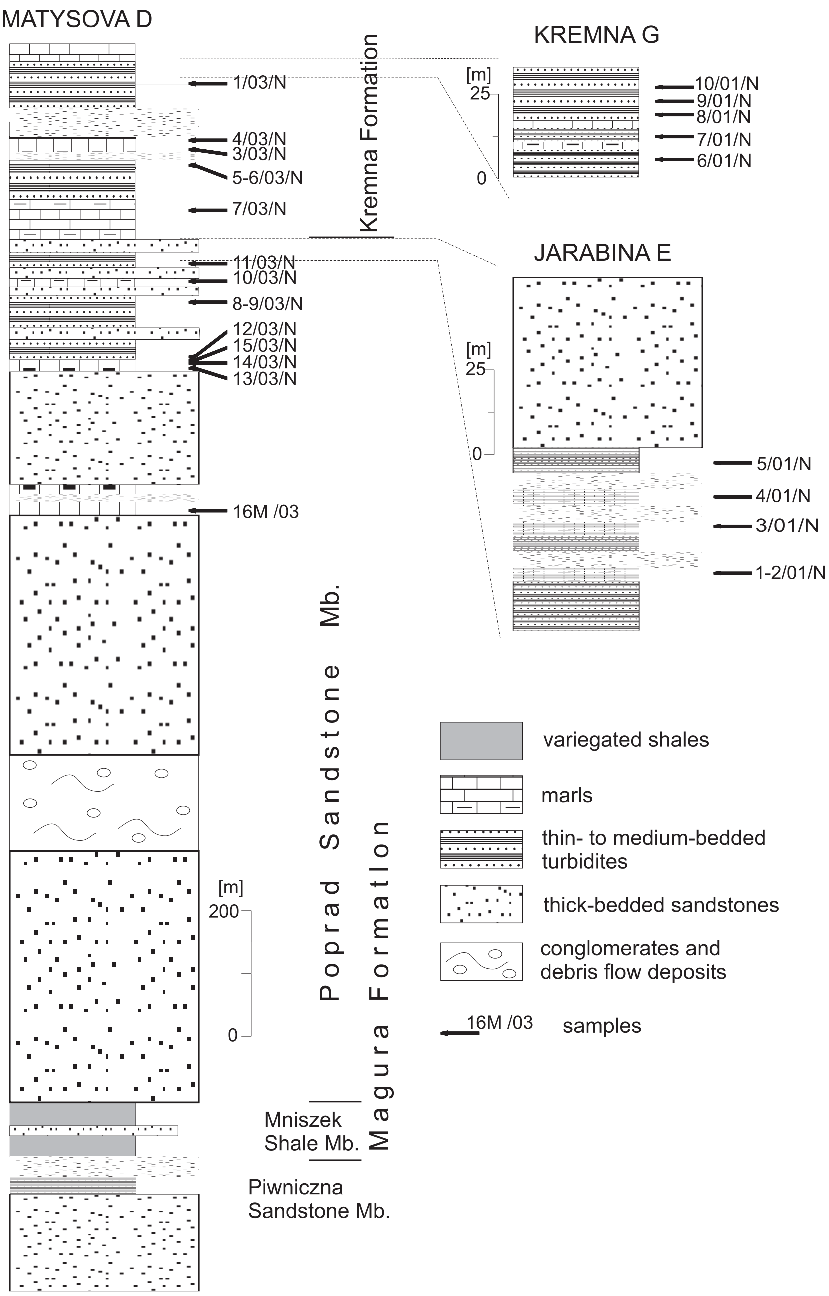

Fig. 9. Lithostratigraphic columns of the Poprad Member of the Magura Formation and Kremna Formation in the Matysova, Jarabina, Hranične and Kremna sections

Riedel*,* *Ericsonia formosa* (Kamptner)*, Neococcolithes dubius* (Deflandre)*, N. minutus* (Perch-Nielsen)*, Reticulofenestra hillae* Bukry et Percival*, R. umbilica* (Levin)*, Sphenolithus moriformis* (Bronnimann et Stradner). The youngest of the species, determining the age of the association, is *Discoaster tanii*.

Leluchów Marls Member. The nannofossil assemblage from sample 13M/02/N is abundant and diverse. Each observation field contains at least 10–15 specimens . The autochthonous association is characterized by the presence of *Chiasmolithus oamaruensis* (Deflandre)*, Coccolithus pelagicus, Coronocyclus nitescens* (Kamptner)*, Cyclicargolithus floridanus, Dictyococcites bisectus, Discoaster deflandrei, D. barbadiensis, D. saipanensis, D. tanii nodifer, D. tanii, Ericsonia formosa, Helicosphaera compacta* Bramlette et Wilcoxon*, H. euphratis* Haq*, Isthmolithus recurvus* Deflandre*, Lanternithus minutus* Stradner*, Neococcolithes dubius, Reticulofenestra callida* (Perch-Nielsen)*, R. hillae, R. reticulata* (Gartner et Smith)*, R. umbilica, Sphenolithus moriformis, Zygrhablithus bijugatus* (Deflandre in Deflandre et Fert). The most abundant are *Cyclicargolithus floridanus, Dictyococcites bisectus* and *Coccolithus pelagicus*. Still abundant but to a lesser extent are *Ericsonia formosa, Reticulofenestra umbilica, R. reticulata* and *Sphenolithus moriformis*. The youngest species determining the age of the sample are *Isthmolithus recurvus, Discoaster barbadiensis* and *D. saipanensis*.

The assemblage of sample 14M/02/N is less abundant in nannofossils, when compared with that of 13M/02/N (5–7 specimens per observation field). The most abundant species are represented by *Dictyococcites bisectus, Cyclicargolithus floridanus, Coccolithus pelagicus, Isthmolithus recurvus* and *Reticulofenestra reticulata*. *Ericsonia formosa* is still present whereas *Discoaster barbadiensis* and *D. saipanensis* are not. Importantly, from the biostratigraphical point of view is the relative abundance of *Ericsonia subdisticha* (Roth et Hay in Hay *et al.*) and *E. fenestrata* (Deflandre et Fert).

The next important biostratigraphical event is the disappearance *of Ericsonia formosa* from sample 15M/82/N. The assemblage still contains both *Reticulofenestra umbilica* and *R. hillae*.

Smereczek Shale Member. The nannofossils are moderately and well preserved and the assemblages show a much lower diversity as well as a lower number of specimens. The sample 16M/02/N lacks *Ericsonia formosa*, whereas *Reticulofenestra umbilica* and *R. hillae* are still present. The frequency of certain species (e.g. *Lanternithus minutus* and *Isthmolithus recurvus*) has decreased. The most abundant species are *Cyclicargolithus floridanus* and *Dictococcites bisectus*.

The following two samples 17M/02/N, 18M/02/N contain an assemblage represented by *Braarudosphaera bigelowii* (Gran et Braarud)*, Coccolithus pelagicus, Coronocyclus nitescens, Cyclicargolithus floridanus, Dictiococcites bisectus, Discoaster deflandrei* Bramlette and Riedel*, Neococcolithes dubius, Pontosphaera multipora* (Kamptner)*, Reticulofenestra dictyoda* (Deflandre *in* Deflandre et Fert)*, R. lockerii* Műller*, R. ornata* Műller*, Sphenolithus moriformis, Transversopontis fibula* Gheta in Gheta *et al.* and *Zygrhablithus bijugatus*. *Reticulofenestra umbilica* and *R. hillae* have not been found. The most important species are *Reticulofenestra lockerii, R. ornata and Transversopontis fibula.*

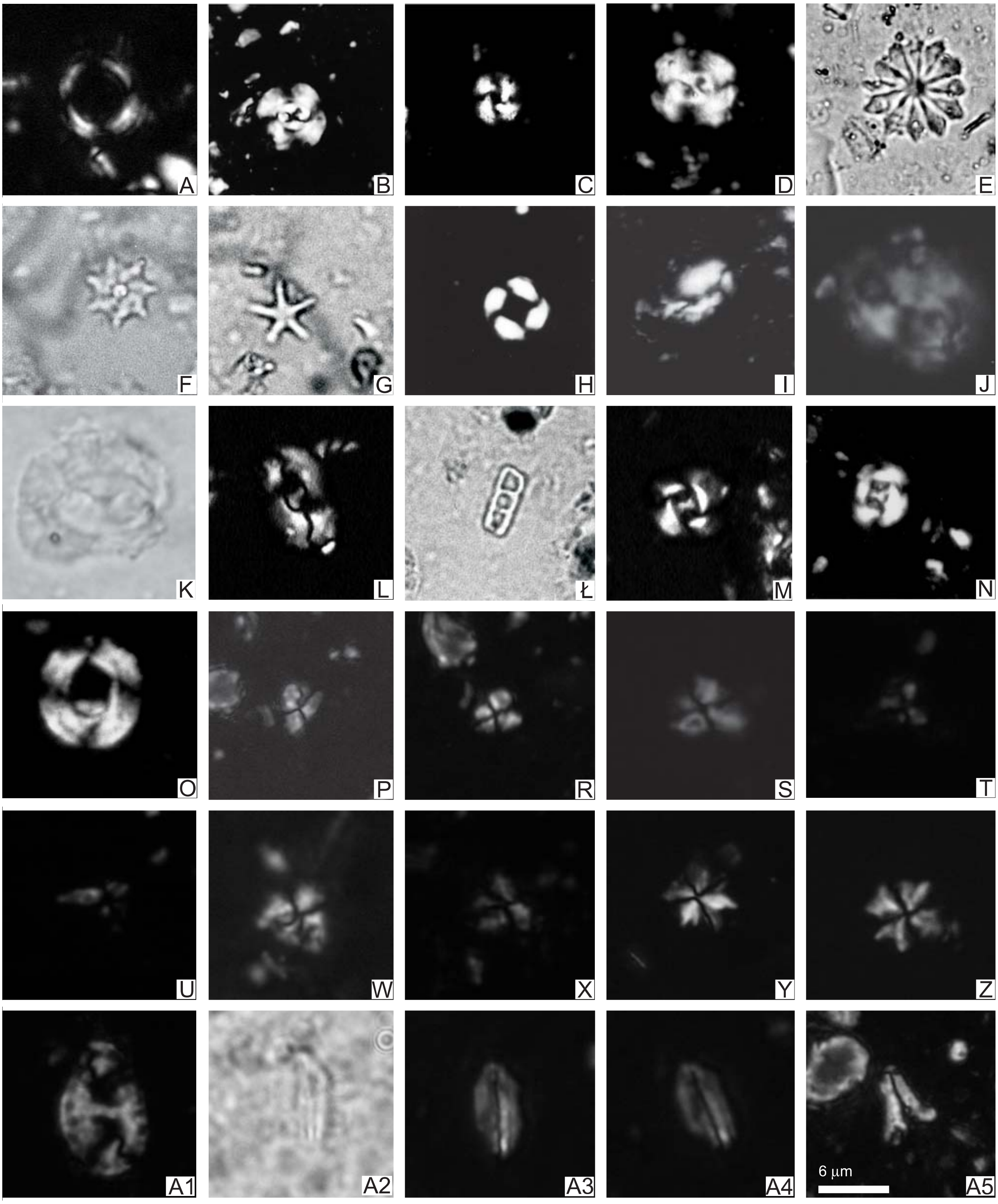

Fig. 10. LM microphotographs of nannofossils form the Ujak Facies, Magura Formation and Kremna Facies

A — *Coronocyclus nitescens*, sample 5/01/N; **B** — *Cyclicargolithus abisectus*, sample 19M/02/N; **C** — *Cyclicargolithus floridanus*, sample 14M/02/N, **D** — *Dictyococcites bisectus*, sample 15/03/N; **E** — *Discoaster barbadiensis*, sample 13M/03/N; **F** — *Discoaster saipanensis*, sample13M/03/N; **G** — *Discoaster tanii*, sample U1301/N; **H** — *Ericsonia formosa*, sample 14M/02/N; **I** — *Helicosphaera carteri*, sample 10/03/N; **J**, **K** — *Helicosphaera compacta*, sample U1201/N; **L** — *Helicosphaera euphratis*, sample 19M/02/N; **Ł** — *Isthmolithus recurvus*, sample 13M/02/N; **M** — *Reticulofenestra daviessi*, sample 5/03/N; **N** — *Reticulofenestra lockerii*, sample 19M/02/N; **O** — *Reticulofenestra umbilica*, sample 16M/02/N; **P**, **R** — *Sphenolithus conicus*, sample 13/03/N; **S** — *Sphenolithus conicus*, sample 14/03/N; **T**, **U** — *Sphenolithus delphix*, sample 5/01/N; **W** — *Sphenolithus disbelemnos*, sample 5/03/N; **X** — *Sphenolithus disbelemnos*, sample 6/01/N; **Y** — *Sphenolithus dissimilis* sample 21M/02/N; **Z** — *Sphenolithus dissimilis*, sample 16/03/N; **A1** — *Transversopontis pulcher*, sample 17M/02/N; **A2**, **A3**, **A4** — *Triquetrorhabdulus challengerii*, sample 10/01/N; **A5** — *Zygrhablithus bijugatus*, sample 7/03/N

Malcov Formation ***ss***. The samples examined from the Leluchów section (19M/02/N, 20M/02/N, 21M/02/N, 22M/02/N) and from Udol, section B (U1–U3/01/N) yield well-preserved and moderately diverse calcareous nannoplankton assemblages that are dominated by placoliths. The autochthonous assemblage is abundant in *Coccolithus pelagicus, Coronocyclus nitescens, Cyclicargolithus abisectus, C. floridanus, Dictiococcites bisectus, Reticulofenestra lockerii, R. ornata*. The presence of *Cyclicargolithus abisectus* and *Sphenolithus dissimilis* is important from a stratigraphical point of view.

YOUNGEST DEPOSITS OF THE MAGURA SUCCESSION

Poprad Member of the Magura Formation. The base of the Poprad Member and, additionally, the uppermost part of the Piwniczna Member were sampled in Milik quarry near Muszyna (see Oszczypko *et al.*, 1990). The abundance pattern varies from more than 15 specimens per observation field in sample 16/03/N, to 5–10 specimens (per observation field) in samples 9/03/N, 4/01/N and 15/03/N. The smallest amount of specimens (less than 5 per observation field) was observed in sample 12/03/N. The nannofossils are quite well preserved, though the assemblages show a low diversity and a low number of specimens. The assemblage described from samples 16–13/03/N (Matysova, Figs. 2A and 9) is characterized by an abundant presence of *Coccolithus eopelagicus, C. pelagicus, Cyclicargolithus floridanus, C. abisectus* (Műller), *Sphenolithus dissimilis* Bukry et Percival, *S. moriformis, S. radians* Deflandre and *S. conicus* Bukry. The latter is not present in sample 16/03/N only. *Dictyococcites bisectus, Reticulofenestra dictyoda, S. dissimilis and Sphenolithus moriformis* are also abundant, but to a lesser extent.

The samples from the Matysova section (8–12/03/N, Fig. 9) show a very low diversity, poorly preserved nannofossil association, whereas the samples from the Jarabina section (4–5/01/N, Figs. 8A, B and 9) contain a relatively rich assemblage. The autochthonous assemblages are abundant in *Coccolithus pelagicus, Cyclicargolithus floridanus* and *Reticulofenestra minuta,* whereas *Sphenolithus conicus, S. dissimillis, Reticulofenestra dictyoda* and *Zygrhablithus bijugathus* are rare. An important feature of this assemblage is that *Cyclicargolithus abisectus* is much less abundant when compared with the above-mentioned samples. Moreover, the assemblages lack *Dictyococcites bisectus*. Additionally, sample 5/01/N contains *Sphenolithus delphix* Bukry.

Kremna Formation. The abundance pattern varies, from more than 15 specimens per observation field in samples 6/01/N and 8/01/N down to 10–20 specimens (per observation field) in samples 5/03/N and 9/01/N. The lowest abundance pattern (less than 5 specimens per observation field) was observed in samples 10/01/N. The autochthonous assemblage consists of: *Coccolithus pelagicus, Coronocyclus nitenscens, Cyclicargolithus floridanus, C. luminis, Discoaster deflandrei, Helicosphaera euphratis, Pontosphaera enormis, P. plana, P. multipora, Reticulofenestra dictyoda, Sphenolithus disbelemnos, S. conicus, S. capricornutus, S. disbelemnos* Fornaciari et Rio and *S. moriformis*. A quantitative assessment of the autochthonous nannoplankton assemblage indicates the domination of placoliths over other morphological types (eg. *asteroliths, sphenoliths*, *helicospheres*).

The assemblage is dominated by *Cyclicargolithus floridanus and Coccolithus pelagicus,* whereas *Reticulofenestra dictyoda, Sphenolithus conicus, S. disbelemnos and S. moriformis* are less common. The youngest species, determining the age of the assemblage, is *Sphenolithus disbelemnos.* Additionally, sample 5/03/N contains *Umbilicosphaera rotula* (Kamptner).

Almost all the samples investigated are highly dominated by reworked species, especially those of Middle/Late Eocene age. The reworking is highest in samples 6/01/N and 5/03/N where reworked taxa represent more than 50% of all determined species, whereas in other samples it decreases considerably, reaching a value not higher than approximately 20–30%. The allochthonous assemblage consists mostly of Middle/Late Eocene species such as: *Blackites spinosus, Chiasmolithus gigas, C. grandis, C. modestus, C. solitus, C. titus, Discoaster barbadiensis, D. distinctus, D. lodoensis, D. saipanensis, D. strictus, D. tanii, Discoaster tanii nodifer, Ericsonia formosa, Helicosphaera bramlettei, H. compacta, H. lophota, Neococcolithes dubius, Reticulofenestra hillae, R. umbilica, Sphenolithus pseudoradians, S. spiniger* and *Zygrhablithus bijugatus*. This assemblage is dominated by coccoliths of the genera *Chiasmolithus*, *Discoaster* and *Sphenolithus*.

BIOSTRATIGRAPHICAL ZONATION

For the purpose of biostratigraphic analysis the standard zonation of Martini (1971) was used. In the case where index species were not been observed it was necessary to use secondary index and characteristic species.

DISCOASTER SAIPANENSIS ZONE (NP17)

D e f i n i t i o n . — the base of the zone is defined by the last occurrence of *Chiasmolithus solitus*, and the top by the first occurrence of *Chiasmolithus oamaruensis*.

A u t h o r . — Martini (1970);.

A g e . — Middle Eocene.

R e m a r k s . — This zone was identified in the Red Shales. From Udol, section A (samples: U13/02/N).

The zonal assignment is based on the FO of *Discoaster tanii*, which is characteristic of the middle part of NP17 (see Bukry, 1973). At the same time both *Chiasmolithus solitus* as well as *C. oamaruensis* do not occur. The FO of the latter is an important biostratigraphical event marking the lower boundary of NP18. Additionally, these samples contain flat specimens of *Neococcolithes minutus*, which are characteristic of the NP17 Zone (Aubry, 1986).

According to E. Malata (in Oszczypko *et al.*, 2004), the foraminiferal assemblage of the red marls consists of abundant agglutinated taxa. There are individual specimens of *Reticulophragmium amplectens* (Grzybowski) and *Praesphaerammina subgaleata* (Vasiček) representing common species of the Middle Eocene. The very rare planktonic foraminifer *Globigerina* ex. gr. *praebulloides* Blow, whose first occurrence is known from the Middle Eocene, confirms a Middle Eocene or younger age.

Table 1

Calcareous nannofossil distribution — Ujak Facies

Lithostratigraphy	LELUCHÓW										UDOL A	UDOL B				
	Leluchów Marls Mb.		Smereczek Shale Mb.				Malcov				Varieg. Marls	Malcov				
Age	Late Eoc.	E/O	Early Oligocene				Early Oligocene				M/L Eoc.	Early Oligocene				
Calcareous nannofossil zones (Martini, 1971)	NP 19–20	NP 21	NP 22	NP 22	NP 23	NP 23	NP 24	NP 24	NP 24	NP 24	NP 17	NP 24	NP 24	NP 24	NP 24	NP 24
sample numbers	13M/ 02/N	14M/ 02/N	15M/ 02/N	16M/ 02/N	17M/ 02/N	18M/ 02/N	19M/ 02/N	20M/ 02/N	21M/ 02/N	22M/ 02/N	U13 01/N	U12 01/N	U3/ 01/N	U4/ 01/N	U1/ 01/N	U2/ 01/N
sample abundance	H	M	L	L	L	L	M	M	M	M	M	H	M	M	M	H
preservation	M	M	P	P	P	P	M	M	M	M	M	M	M	M	M	M
B. bigelowii				X	X	X	X									
Chiasmolithus medius				X												
Ch. oamaruensis	X			X												
Chiasmolithus sp.		X														
Coccolithus eopelagicus												X	X	X	X	
C. pelagicus	X	X			X	X	X	X	X	X	X	X	X	X	X	
Coronocyclus nitescens	X		X	X												
Cyclagelosphaera alta																
Cyclic. abisectus							X	X	X	X		X	X	X	X	
Cyclic. floridanus	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Dictyococcites bisectus	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Dictyococcites sp.	X	X		X												
Discoaster barbadiensis	X										X	R			R	
D. deflandrei	X	X	X	X			X				X	X				
D. saipanensis	X															
D. sp.	X	X		X												
D. tanii		X		X				X			X	X				X
D. tanii nodifer	X			X		X	X									
Ericsonia fenestrata		X			X		X									
E. formosa	X	X				R	R	R	R		X	R				
E. sp.	X	X		X												
E. subdisticha		X		X												
F. tympaniformis		X														
Helicosphaera careteri												X				
H. compacta	X			X								X	X			
H. euphratis	X						X					X				
Isthmolithus recurvus	X	X	X	X	R	R	R					R	R			R
Lanternithus minutus			X	X	R		R									
Neococcolithes dubius		X				X	X									
Pontosphaera multipora	X				X		X									
Reticulofenestra callida		X	X													
R. dictyoda	X	X	X	X			X			X	X	X				X
R. hillae	X	X	X				R	R				R				R
R. lockerii					X	X	X									
R. ornata					X	X	X			X		X				X
R. reticulata	X	X	X	X	R		R									
R. umbilica	X	X	X	X			R	R		R	X	R				R
Rhabdosphaera gladius	X	X	X	X												
Sphenolithus dissimilis									X			X	X	X	X	X
Sph. moriformis		X	X	X	X		X	X				X	X	X		X
Sph. predistentus		X	X	X												
Sph. radians				X												X
Sph. spiniger		X		X			X									

Tab. 1 continued

Lithostratigraphy	LELUCHÓW										UDOL A	UDOL B				
	Leluchów Marls Mb.			Smereczek Shale Mb.			Malcov				Varieg. Marls	Malcov				
Age	Late Eoc.	E/O	Early Oligocene				Early Oligocene				M/L Eoc.	Early Oligocene				
Calcareous nannofossil zones Martini, 1971	NP 19–20	NP 21	NP 22	NP 22	NP 23	NP 23	NP 24	NP 24	NP 24	NP 24	NP 17	NP 24	NP 24	NP 24	NP 24	NP 24
sample numbers	13M/ 02/N	14M/ 02/N	15M/ 02/N	16M/ 02/N	17M/ 02/N	18M/ 02/N	19M/ 02/N	20M/ 02/N	21M/ 02/N	22M/ 02/N	U13 01/N	U12 01/N	U3/ 01/N	U4/ 01/N	U1/ 01/N	U2/ 01/N
sample abundance	H	M	L	L	L	L	M	M	M	M	M	H	M	M	M	H
preservation	M	M	P	P	P	P	M	M	M	M	M	M	M	M	M	M
Transversopontis fibula					X											
Trans. obiquipons				X	X		X									
Trans. pulcher					X			X				X				
Trans. pulcheroides				X								X				
Zygrhablithus bijugatus	X	X	X	X	X		X					X	X	X	X	X

B. — *Braarudosphaera*, *Cyclic.* — *Cyclicargolithus*, *F.* — *Fasciculithus*; estimated abundance of nannofossils in samples: H — high (>15 specimens/one field of view), M — moderate (15–5 specimens/one field), L — low (1–5 specimens/one field); preservation of nannofossils: M — moderate (overgrowth, etching or mechanical damage is apparent but majority of specimens are easily identifiable), P — poor (etching and mechanical damage is intensive making identification of some specimens difficult); categories after Burnett and Whitham (1999), modified; X — autochtonous species, R — redeposited species

ISTHMOLITHUS RECURVUS AND *SPHENOLITHUS PSEUDORADIANS* COMBINED INTERVAL ZONE (NP19–20)

D e f i n i t i o n . — The base of the zone is defined by the first occurrence of *Isthmolithus recurvus* and the top by the last occurrence of *Discoaster saipanensis* and/or *Discoaster barbadiensis*.

A u t h o r . — Aubry (1983).

A g e . — Late Eocene.

R e m a r k s . — This zone was identified in the following lithostratigraphical units of the Leluchów Marl Mb. (13M/02/N).

The zonal assignment is based on a co-occurrence of *Isthmolithus recurvus*, *Discoaster barbadiensis*, *D. saipanensis* and *Reticulofenestra reticulata*. Such an association is typical of the Interval Zone NP19–20. *Ericsonia formosa*, whose last occurrence indicates the upper limit of Zone NP 21, was also observed.

ERICSONIA SUBDISTICHA ZONE (NP21)

D e f i n i t i o n . — The base of the zone is defined by the last occurrence of *Discoaster saipanensis* and/or *D. barbadiensis*, and the top by the last occurrence of *Ericsonia formosa*.

A u t h o r . — Roth and Hay in Hay *et al.* (1967), emend. Martini (1970).

A g e . — Early Oligocene (Late Eocene/Early Oligocene *cf.* Cavelier, 1979).

R e m a r k s . — This zone was identified in the Leluchów Marl Mb. (sample 14M/02/N).

The zonal assignment is based on the continuous range of *Ericsonia formosa*, following the disappearance of *Discoaster saipanensis* and *D. barbadiensis*. Furthermore, the assemblages of this zone are characterized by a more frequent occurrence of *Isthmolithus recurvus* than in NP19–20. According to a number of authors (Monenechi, 1986; Perch-Nielsen *et al.*, in Pomerol and Premoli-Silva, 1986; Backman, 1987; Nocchi *et al.*, 1988*b*; Krhovský *et al.*, 1992) such an increase in *Isthmolithus recurvus* is a characteristic biostratigraphic event at, or just below, the Eocene/Oligocene boundary.

HELICOSPHAERA RETICULATA ZONE (NP22)

D e f i n i t i o n . — The base of the zone is defined by the last occurrence of *Ericsonia formosa*, and the top by the last occurrence of *Reticulofenestra umbilica*.

A u t h o r s . — Bramlette and Wilcoxon (1967), emend Martini (1970).

A g e . — Early Oligocene.

R e m a r k s . — This zone was identified in the Leluchów Marl Mb. (sample 15M/02/N) and in the Smereczek Shale Mb. (sample 16M/02/N).

The zonal assignment is based on the continuous range of *Reticulofenestra umbilica* following the disappearance of *Ericsonia formosa*. At the same time *Reticulofenestra ornata* and *Transversopontis fibula* were not found.

SPHENOLITHUS PREDISTENTUS ZONE (NP23)

D e f i n i t i o n . — The base of the zone is defined by the last occurrence of *Reticulofenestra umbilica*, and the top is defined by the first occurrence of *Sphenolithus ciperoensis*.

A u t h o r . — Bramlette and Wilcoxon (1967), emend Martini (1970).

A g e . — Middle Oligocene.

R e m a r k s . — This zone was identified in the Smereczek Shale Mb. (samples: 17 M–18M/02/N.

The zone assignment is due to the co-occurrence of abundant *Reticulofenestra ornata*, *Transversopontis fibula* and *Reticulofenestra lockerii*, following the disappearance of *R.*

Table 2

Calcareous nannofossil distribution — Magura and Kremna formations

Lithostratigraphy	MATYSOVA									HRA-NICNE	JARABINA		MATYSOVA							KREMNA				
	Magura Fm.												Kremna Fm.											
Age	Oligocene												O/M	Miocene										
Calcareous nannofossil zones Martini (1971)	NP 24/25	25	25	NP 25	NN 1	NN 1	NN 1	NN 1	NN 1	NN 1		NN 1	NN 1	NN 1		NN 2				NN 2		NN 2	NN 2	NN 2
sample numbers	16/ 03/N	13/ 03/N	14/ 03/N	15/ 03/N	12/ 03/N	9/ 03/N	8/ 03/N	10/ 03/N	11/ 03/N	11/ 01/N	1-3/ 01/N	4/ 01/N	5/ 01/N	7/ 03/N	6/ 03/N	5/ 03/N	3/ 03/N	4/ 03/N	1/ 03/N	6/ 01/N	7/ 01/N	8/ 01/N	9/ 01/N	10/ 01/N
sample abundance	H	M	M	M	L	M	M	M		L		M	M	L		M	VL	VL		H		H	M	L
nannofossil preservation	M	M	M	M	P	P	P	P		P		M	P	P		M	VP	VP		M		M	M	P
Braarudosphaera bigelowii	X		X	X				X	-		-			X	-	X			-	X	-			
Chiasmolithus medius									-		-				-				-		-		R	
Chiasmolithus gigas	R		R			R	R	R	-		-				-				-		-			
Chiasmolithus grandis									-	R	-				-				-	R	-		X	R
Coccolithus eopelagicus	X	X	X	X			X	X	-		-	X		X	-	X			-	x	-	X	x	
Coccolithus pelagicus	X	X	X	X		X	X	X	-	X	-	X	X	X	-	X	X	X	-	X	-	X	x	
Coronocyclus nitescens	X					X			-		-		X		-				-		-			
Cyclicargolithus abisectus	X	X	X	X	X	X			-	X	-	X			-	R			-		-	R		
Cyclicargolithus floridanus									-		-				-		X	X	-		-			
Dictyococcites bisectus	X	X	X	X					-		-				-				-	R	-			
Discoaster barbadiensis	R								-	R	-	R			-				-		-		R	
Discoaster binodosus						R	R	R	-		-				-	R			-	R	-			
Discoaster deflandrei	X	X						X	-		-		X		-				-		-			X
Discoaster multiradiatus	R					R	R	R	-		-				-	R			-		-			
Discoaster saipanensis									-		-				-				-	R	-		R	
Discoaster salisburgensis		R					R		-		-				-	R			-	R	-			
Discoaster tanii									-		-				-				-		-	R		
Discoaster sp.									-		-				-				-		-	X		
Ericsonia fenestrata								X	-		-			X	-				-	X	-			
Ericsonia formosa							R	R	-	R	-		R		-	R			-	R	-	R		R
Ericsonia subdisticha									-		-				-				-		-			
Helicosphaera carterii								X	-		-				-				-		-			
Helicosphaera compacta									-		-	X			-				-	X	-	X	X	
Helicosphaera euphratis									-		-				-				-		-	X	X	
Helicosphaera heezenii									-		-		R		-				-		-			
Helicosphaera papilata									-		-		X		-				-		-			
Isthmolithus recurvus						R		R	-		-				-				-		-	R		

Pontosphaera lateliptica		X							-		-				-				-		-			
Pontosphaera multipora		X						X	-		-				-	X			-		-	X		
Pontosphaera plana						X			-		-				-				-		-			
Reticulofenestra daviessi						X			-		-				-	X			-		-			
Reticulofenestra dictyoda						X			-		-				-	X			-		-			
Reticulofenestra minuta						X			-		-			X	-	X			-		-	X		
Reticulofenestra ornata	X				X				-		-			X	-				-		-			
Sphenolithus calyculus	X								-	X	-				-				-		-	X		
Sphenolithus conicus		X	X			X	X	X	-	X	-	X	X		-	X			-	x	-		X	X
Sphenolithus delphix									-		-		X		-				-		-			
Sphenolithus disbelemnos									-		-				-	X			-	x	-	X	X	X
Sphenolithus dissimilis	X	X	X	X		X	X	X	-	X	-	X	X	X	-	X			-	X	-	X		
Sphenolithus moriformis	X	X	X	X		X	X	X	-		-	X	X		-	X		X	-	X	-			X
Sphenolithus radians									-		-	X			-	X			-	X	-	X	X	
Transversopontis fibula									-		-				-				-	R	-	R	R	
Transversopontis obiquipons									-		-				-				-		-			
Transversopontis pulcher									-		-				-				-	X	-	X	X	
T. pulcheroides	X								-	X	-				-				-	X	-		X	
T. challengerii									-		-				-				-		-	X		X
Umbilicosphaera rotula									-		-				-	X			-		-			
Zygrhablithus bijugatus	X	X		X	X	X		X	-	X	-	X	X	X	-				-					

Estimates of the abundance of nannofossils in samples: VL = very low (< 1 specimens/1 field); preservation of nannofossils: VP = very poor (identification of some specimens is impossible); other explanations see Table 1

umbilica. Such an association of species is characteristic of the equivalent of Zone NP23 in the Paratethys region.

SPHENOLITHUS DISTENTUS ZONE (NP24)

D e f i n i t i n . — The base of the zone is defined by the first occurrence of *Sphenolithus ciperoensis*, and the top by the last occurrence of *S. distentus*.

A u t h o r s . — Bramlette and Wilcoxon (1967).

A g e . — Late Oligocene.

R e m a r k s . — This zone was identified in the Malcov Fm. from the Leluchów section (samples: 19M–22M/02/N) and from the Ujak section (samples: U1–U4/01/N, U12/01/N).

The FO of *Cyclicargolithus abisectus* is usually found close to the FO of *Sphenolithus ciperoensis* (zonal marker for the lower boundary of Zone NP24) and thus can be used to approximate the boundary between NP23 and NP24 (Martini and Műller, 1986). In addition, *Sphenolithus dissimilis* was also observed. The FO of these species is characteristic of Zone NP24 (see Perch-Nielsen, 1985).

SPHENOLITHUS CIPEROENSIS ZONE (NP25)

D e f i n i t i o n . — The base of the zone is defined by the last occurrence of *Sphenolithus distentus*, and the top by the last occurrence of *Helicosphaera recta* and/or *Sphenolithus ciperoensis*.

A u t h o r s . — Bramlette and Wilcoxon (1967), emend. Martini (1976).

A g e . — Late Oligocene.

R e m a r k s . — This zone was identified in the Magura Fm. from the Matysova section (samples: 13–15/03/N).

The assignment of Zone NP25 is based on the first occurrence of *Sphenolithus conicus*, and the continuous range of *Cyclicargolithus abisectus*, *Dictyococcites bisectus* and *Zygrhablithus bijugatus*. The FO of *Sphenolithus conicus* has been traditionally used as the base of Zone NN1. However, Bizon and Műller (1979), Biolzi *et al.* (1981) and Melinte (1995) have observed the FO of these species as low as in the upper part of Zone NP25. The top of NP25 was considered for a long time as the Oligocene/Miocene boundary though, according to Berggren *et al.* (1995), this boundary lies within Zone NN1. The Oligocene/Miocene boundary is characterised by the extinction of *Sphenolithus ciperoensis* (lower latitudes) and *Dictyococcites bisectus* (higher latitudes) (Perch-Nielsen, 1985; Berggren *et al.*, 1995; Fornaciari and Rio, 1996; Young in Bown, 1998).

TRIQUETRORHABDULUS CARINATUS ZONE (NN1)

Definition. — The base of the zone is defined by the last occurrence of *Helicosphaera recta* and/or *Sphenolithus ciperoensis*, and the top by the first occurrence of *Discoaster druggii*.

Authors. — Bramlette and Wilcoxon (1967), emend Martini and Worsley (1970).

Age. — Early Miocene and/or latest Oligocene.

Remarks. — This zone was identified in the following lithological units: the Magura Fm. from the Matysova section (samples: 10–12/03/N) and the Kremna section (samples: 4–5/03/N), and the Kremna Fm. from the Matysova section (sample 7/03/N).

The zonal assignment is based on the continuous range of *Sphenolithus conicus*, *S. dissimillis* and *Triquetrorhabdulus carinatus*, following the disappearance of *Dictyococcites bisectus*. It was recommended for many years to use the LO of *Sphenolithus ciperoensis* in order to define the base of NN1, as used in the Okada and Bukry (1980) zonation for the base of their CN1 Zone. However, this species is common in low lattitudes and almost absent in higher ones. Therefore, Perch-Nielsen (1985), Berggren *et al.* (1995), Fornaciari *et al.*, (1996) and Young (in Bown, 1998) suggested redefining the base of NN1 as the LO of *Dictyococcites bisectus*.

The biostratigraphic range of *Sphenolithus delphix* is still problematic. This taxon was reported by Aubry (1985) from NP25 and NN1 though, according to Young (Young in Bown, 1998), this species is characteristic only of the upper part of NN1, which really marks the Oligocene/Miocene boundary.

The rare occurrence of *Sphenolithus conicus* as well as the lack of *Sphenolithus delphix* may suggest that the nannofossil assemblage of sample 7/03/N (Kremna) belongs to the highest part of Zone NN1. In addition this assemblage did not contain *Sphenolithus disbelemno*s nor *Discoaster druggii*.

DISCOASTER DRUGGII ZONE (NN2)

Definition. — the base of the zone is defined by the first occurrence of *Discoaster druggii*, and the top by the last occurrence of *Triquetrorhabdulus carinatus*.

Authors. — Martini and Worsley (1970).

Age. — Early Miocene.

Remarks. — This zone was identified in the Kremna Fm. from the Matysova section (sample 5/03/N) and the Kremna section (samples: 8–10/01/N).

The zonal assignment is based on the co-occurrence of the following species: *Sphenolithus conicus, S. disbelemnos*, *Reticulofenestra pseudoumbilica* and *Triquetrorhabdulus carinatus*. According to the standard zonation of Martini (1971) and Martini and Worsley (1970), the first occurrence of *Reticulofenestra pseudoumbilica* takes place in NN5. However, this taxon was reported by Marunteanu (1992) from the lower limit of NN2. According to Young (in Bown, 1998), the FO of *Sphenolithus disbelemnos* and/or *Umbilicosphaera rotula* is a reliable biostratigraphical event characteristic of the lower limit of NN2 Zone.

LITHOSTRATIGRAPHIC CORRELATION

In the Krynica Subunit, there has always been a problem as to how to separate the Piwniczna and Poprad Sandstone members of the Magura Formation when the Mniszek Shale Member was absent. As a result the thickness of the Piwniczna Sandstone Member was often overestimated. Sometimes the Kowaniec Beds were regarded as an equivalent of the Mniszek Shale Member. In fact, these units were never biostratigraphically correlated. In cases where the Mniszek Shale Member is not present, we have proposed separating these two sandstone members using a different criterion: namely, the presence or absence of calcareous mudstones. The Piwniczna Sandstone Member should be regarded as a succession of thick-bedded sandstones with intercalations of non-calcareous mudstones, and the Poprad Sandstone Member as a similar succession but with intercalations of calacareous mudstones.

In the part of the Krynica Subunit studied the Poprad Sandstone Member was mapped only in the Piwniczna (Mniszek, Hanuszów) and Żegiestów–Andrzejówka areas. We consider that, the occurrence of this member is much wider and probably forms the wide syncline, situated south of the Gorce Range, between Pieniążkowice and Kluszkowce. It is for this reason that similar lithofacies, which have been described as the Malcov Beds from the Nowy Targ area (Cieszkowski and Olszewska, 1986; Cieszkowski, 1992) are in fact the Poprad Sandstone facies. These sandstones were also penetrated by the Nowy Targ PIG 1 borehole (Paul and Poprawa, 1992).

In the area of Matysova and Hranične, the uppermost part of the Poprad Sandstone Member is composed of packages of calcareous greyish mudstones resembling the Łącko Marls. In the light of this it is important to revise the age and position of the Frydman Formation and of the Kowaniec Beds (see Alexandrowicz *et al.*, 1984; Birkenmajer and Oszczypko, 1989).

The newly-established Kremna Formation (Lower Miocene) should be correlated with other Lower Miocene deposits known from the contact zone between the Magura Nappe and the PKB (Cieszkowski, 1992), and from the Nowy Targ PIG 1 borehole (Paul and Poprawa, 1992). Similar deposits are also known from the peri-PKB zone in the Humenne area (Matašovsky and Andreyeva-Grigorovich, 2002).

The nannoplankton assemblages from the Kremna Formation can be best compared and correlated with those of the Zawada Fm. (Oszczypko *et al.*, 1999; Oszczypko-Clowes, 2001; Oszczypko and Oszczypko-Clowes, 2002). The calcareous nannofossil association from the lowermost part of the Zawada Fm. includes: *Cyclicargolithus abisectus*, *C. floridanus*, *Sphenolithus conicus*, *Sp. dissimillis*, *Sp. delphix* and *Triquetrorhabdulus carinatus*. Such an association, in the absence of *Dictyococcites bisectus*, is believed to be indicative of the NN1 Zone marking exactly the Oligocene/Miocene boundary. The upper part of the Zawada Fm. was assigned to Zone NN2 on the presence of *Sphenolithus disbelemnos*, *Discoaster druggii* and *Reticulofenestra pseudoumbilica* (Oszczypko *et al.*, 1999; Oszczypko-Clowes, 2001; Oszczypko and Oszczypko-Clowes, 2002).

PALAEOGEOGRAPHICAL AND STRUCTURAL IMPLICATIONS — A DISCUSSION

The present-day structure of the PKB is the result of several tectonic events, which took place during the Late Cretaceous to Mid Miocene time span. According to Birkenmajer (1970, 1977, 1986, 1988, 2001) the main stage of folding and thrusting in the PKB took place during the late Campanian and Maastrichtian, with the exception of the Czorsztyn sub-basin, which was folded during the latest Maastrichtian. These movements produced the nappe structure of the PKB, partly below sea level. Recently, in the Lesnica section, near Haligovce (Czorsztyn succession) the Maastrichtian age of the Jaworki (Puchov) and lower part of the Jarmuta formations was documented by foraminifer and nannoplankton studies (Potfaj, 2002).

The Jarmuta Formation represents varieties of different deposits formed by submarine gravity flows: olistostromes, debris flow-breccias and pebbly mudstones as well as high to low density carbonate/siliciclastic turbidites. In the Udol area, small Mesozoic klippen are dispersed mainly within the Paleocene-Lower Eocene Jarmuta and Proč formations. This may suggest that some of these klippen are large olistostromes. These paraconglomerates are composed mainly of pebbles of Jurassic and Neocomian carbonates and radiolarites derived from different successions of the PKB (Birkenmajer and Wieser, 1990; Mišík *et al*., 1991b). Locally at the base of the Jarmuta and Proč formations, there occur sedimentary breccias composed exclusively of angular fragments and cobbles of PKB Mesozoic rocks. These sedimentary breccias, known as the "cliff breccia" (Birkenmajer, 1985) or the Gregorianka breccia (Nemčok, 1990*a*, *b*; see also Oszczypko *et al*., 2004), probably originated as debris flows, connected with the final stage of the Maastrichtian gravitational submarine sliding (see Birkenmajer, 1979; Golonka and Rączkowski, 1984; Jurewicz, 1997). The deposition of the Jarmuta and Proč formations was triggered by Paleocene uplift of the Magura/PKB source area. These formations were supplied both from the uplifted exotic block (Exotic Andrusov Ridge, see Birkenmajer, 1986, 1988) and also from emerged fragments of the inner part of the PKB (Książkiewicz, 1977). On the submerged blocks of the PKB shallow marine biohermal limestones developed. The clasts of these limestones are dispersed in the Jarmuta, Proč and Szczawnica formations.

In the Magura succession the Jarmuta Formation is succeeded by younger flysch deposits, whereas in the East Slovakian sector of the PKB (the Udol-Plaveč and Inovce areas) the Proč Formation is followed by Lower-Middle Eocene variegated shales (Stranik and Hanzliková, 1968; Leško and Samuel, 1968; Nemčok, 1990*a*, *b*). A deepening of the basin has also been reported from the Myjava-Brezova Basin (Salaj, 1987). This narrow sedimentary area is located in a back-arc basin position (Fig. 11). At the end of the Early Eocene in the southern part of the Magura Basin the development of the deep-water submarine fan began, and this was filled with the channel-lobe turbidite system of the Krynica Member of the Zarzecze Formation and the Piwniczna Sandstone Member of the Magura Formation. This depositional system was supplied from the SE, more or less parallel to the basin axis.

These deposits are rich in exotic rock fragments (Oszczypko, 1975; Marschalko, 1975; Mišík *et al.*, 1991*a*). The rock fragments are composed mainly of granitoids, gneisses, phyllites and quartzites, with a relatively small amount of basic volcanic rocks and Mesozoic carbonates. These exotic clasts in the Eocene deposits from the Krynica Zone differ substantially from those of the Paleocene/Lower Eocene (Jarmuta and Proč formations), dominated by PKB carbonate clasts and volcanic clasts derived from exotic Andrusov Ridge, while the Eocene material of the Krynica Zone is composed of fragments of crystalline rocks, that are derived from continental crust, and infrequent clasts of Mesozoic deep and shallow-water limestones as well as Paleocene/Lower Eocene reef limestones (Myjava succession ?). This suggests a provenance of clastic material type from the Inner Carpathian source area located on the SE margin of the basin. In this case we must accept the transfer of clastic material to the Magura Basin via the Pieniny Klippen Belt.

In the Krynica Zone of the Magura Basin the deposition of the Piwniczna Sandstone Member was followed by variegated shales of the Mniszek Member (Fig. 9) and then by Upper Eocene-Lower Oligocene Submenilite *Globigerina* Marls (Oszczypko-Clowes, 2001), known also from the Ujak and Inovce facies, as well as from the Myjava development (Salaj, 1987). This event recorded the shallowing of the Magura/PKB Basin (see Oszczypko, 2004), which culminated in the Early Oligocene isolation (Menilite Shales) of the basin from the open sea. Parallel to the deposition of the *Globigerina* Marls and, then, Menilite Shales there also occurred the deposition of the Poprad Sandstone Member of the Magura Formation. These palaeogeographical changes have been correlated with the Illyrian movements (Książkiewicz and Leško, 1959; Stranik and Hanzliková, 1968).

The Late Eocene–Early Oligocene reorganization of the basin along the Pieniny Klippen Belt suture zone resulted in the development of two sedimentary areas on both sides of the PKB (Fig. 11): the Central Carpathian Paleogene Basin (CCPB) south of the PKB, and the Magura Basin north of the PKB. During the Mid Eocene to early Burdigalian the CCPB was the site of proximal and distal flysch deposition. In the Magura sedimentary area, during the Late Eocene–Early Oligocene three main facies developed. From the SW to NE these are:

1. The Malcov (Ujak) facies, which occupied the isolated areas inside the PKB, along the PKB/Magura Nappe boundary, and inside the Krynica and Bystrica zones of the East Slovakian sector (Oszczypko, 1973),
2. The Poprad Sandstone Member in the Rača and partly in the Krynica Zone,
3. Glauconitic sandstones and marly pelites (Wątkowa and Budzów beds) in the Siary Zone. The clastic material of the Ujak and Poprad facies was derived from the SE, whereas glauconitic sandstones of the Siary Zone were from the NW and NE (Silesian Ridge).

At that time, according to Marschalko (1975) and Mišik *et al.* (1991*a*), two parallel basins coexisted in the E Slovakian sector (Magura/PKB and CCPB) that were supplied from different source areas. The deposition of the Ujak (Malcov) facies in the Magura/PKB Basin probably reflected periods when the Magura/PKB and CCPB were partly connected. Taking into

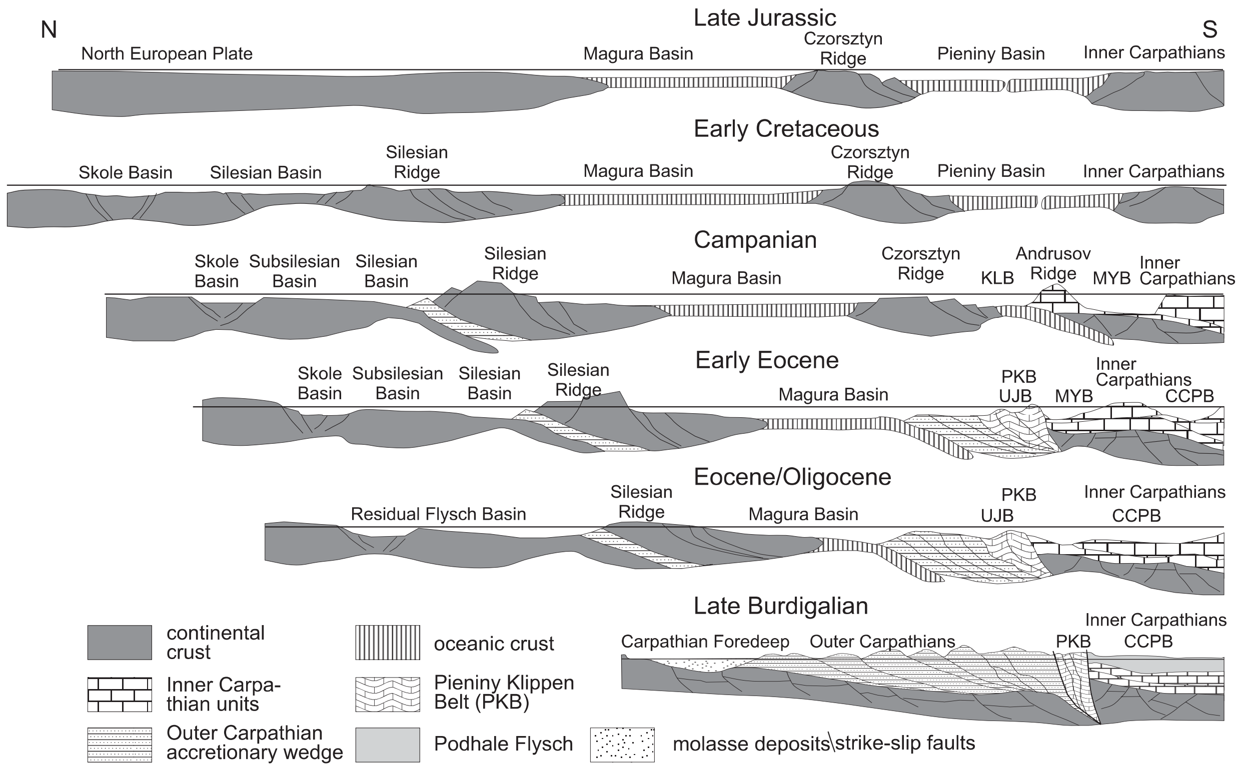

Fig. 11. The Late Jurassic-Late Burdigalian palinspastic evolution model of the Western Carpathians after Oszczypko (1999), modified

KLB — Klape Basin, MYB — Myjava Basin, CCPB — Central Carpathian Paleogene Basin, UJB — Ujak Basin

account the facies distribution and the diameter of the clasts we can conclude that the position of the CCPB source area was located somewhere near Uzhhorod (Sotak *et al.*, 1996). The Magura/PKB source area was probably located at least 100 km south-eastwards in the area now buried beneath the Inner Carpathian/Inner Dacide front (Oszczypko, 2004).

According to Plašienka (2002, 2003) the Early to Mid Eocene collapse of the Inner Carpathians and development of the CCPB was synchronous with the compressional event in the frontal part of the orogenic wedge, resulting in exhumation of the Mesozoic basement of the Magura Basin ("South-Magura Cordillera", see Mišik *et al.*, 1991*a*). Following Oszczypko (2004) the collapse of the Inner Carpathians explains also the deep-water deposition in the PKB, and enabled the transfer of coarse clastic material via the PKB to the Magura Basin, from the source area located in the SE part of the Inner Carpathian/Inner Dacide domain.

After the Late Oligocene folding, the Magura Nappe was thrust northwards and during the Burdigalian its front reached the S part of the Silesian Basin. The early Burdigalian rise in sea level enabled the connection between the Magura piggy-back basin and the Vienna Basin *via* Orava (Oszczypko *et al.*, 1999; Oszczypko-Clowes, 2001; Oszczypko and Oszczypko-Clowes, 2002). In the Magura piggy-back basin deposition of Kremna facies occurred close to the PKB and the Zawada Formation in the more northern part of the basin. During the early Burdigalian there probably existed a marine connection between the Central Carpathians and the PKB/Magura Basin.

The terminal flysch deposition in the Krosno Basin and the Magura piggy-back-basin was followed by the Intra-Burdigalian folding, uplift and overthrust of the Outer Carpathians on to the foreland platform (Oszczypko, 1998, Kovač *et al.*, 1998; Kovač and Plašenka, 2002). This was connected with the collision between the European Plate and overriding Alcapa and Tisza-Dacia microplates (Oszczypko, 1998; Golonka *et al.*, 2000; Golonka, 2004).

CONCLUSIONS

1. In the contact zone between the Magura Nappe and Pieniny Klippen Belt close to the Polish/Slovakian border two new lithostratigraphic units of Krynica Subunit have been established, the Poprad Member of the Magura Formation (Late Eocene to Late Oligocene) and the Kremna Formation (Early Miocene).

2. In the Krynica Subunit of the Magura and Pieniny Klippen Belt the Late Eocene-Oligocene Malcov Formation has been documented.

3. During the Maastrichtion–earliest Paleocene, collision of the Inner Carpathians terranes with the Czorsztyn Ridge and closure of the Pieniny Klippen Belt Basin took place.

4. These movements triggered deposition of the Jarmuta and Proč formations along the northern edge of the PKB.

5. The Late Eocene–Early Oligocene reorganization of the basin located along the Pieniny Klippen Belt suture zone resulted in the development of two sedimentary areas on both sites of PKB: the Central Carpathian Paleogene Basin south of the PKB, and the Magura Basin north of the PKB.

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